

## **Design of Bins and Feeders**

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PT 97/14241/E

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## **1. INTRODUCTION**

Looking at the flow sheet of the cement process (Fig. 1) the importance of bulk solid storage in bins and silos becomes evident. Bins and silos are installed either

- ◆ as *intermediate stores* as to compensate for differences in material demand of subsequent processes (e.g. clinker and cement silos) or
- ◆ as *feed bins* installed for feed rate control (e.g. feed bins for raw, coal and cement mills)

Bins have been considered for too a long time as unimportant and cheap equipment when compared to mill and kiln systems. They have been considered to be simple containments only which are required to be fed with product for storage with the aim that this product may be reclaimed later at a given time at a consistent rate. The physical product characteristics have typically been ignored in bin design with exception of the angle of repose which may have been considered by using slightly steeper wall inclination for a bin's discharge hopper. Making optimum use of a given area was the prime design criteria. So it is not surprising that operation of many bin installations is still impaired by too flat concrete discharge hoppers designed with a too small outlet and equipped with inappropriate feeders.

Operation problems as

- ◆ erratic or even interrupted product flow out of bins with cohesive bulk solids,
- ◆ flushing of the feeders with powders,
- ◆ product segregation,
- ◆ incomplete emptying resulting in a reduced bin live capacity

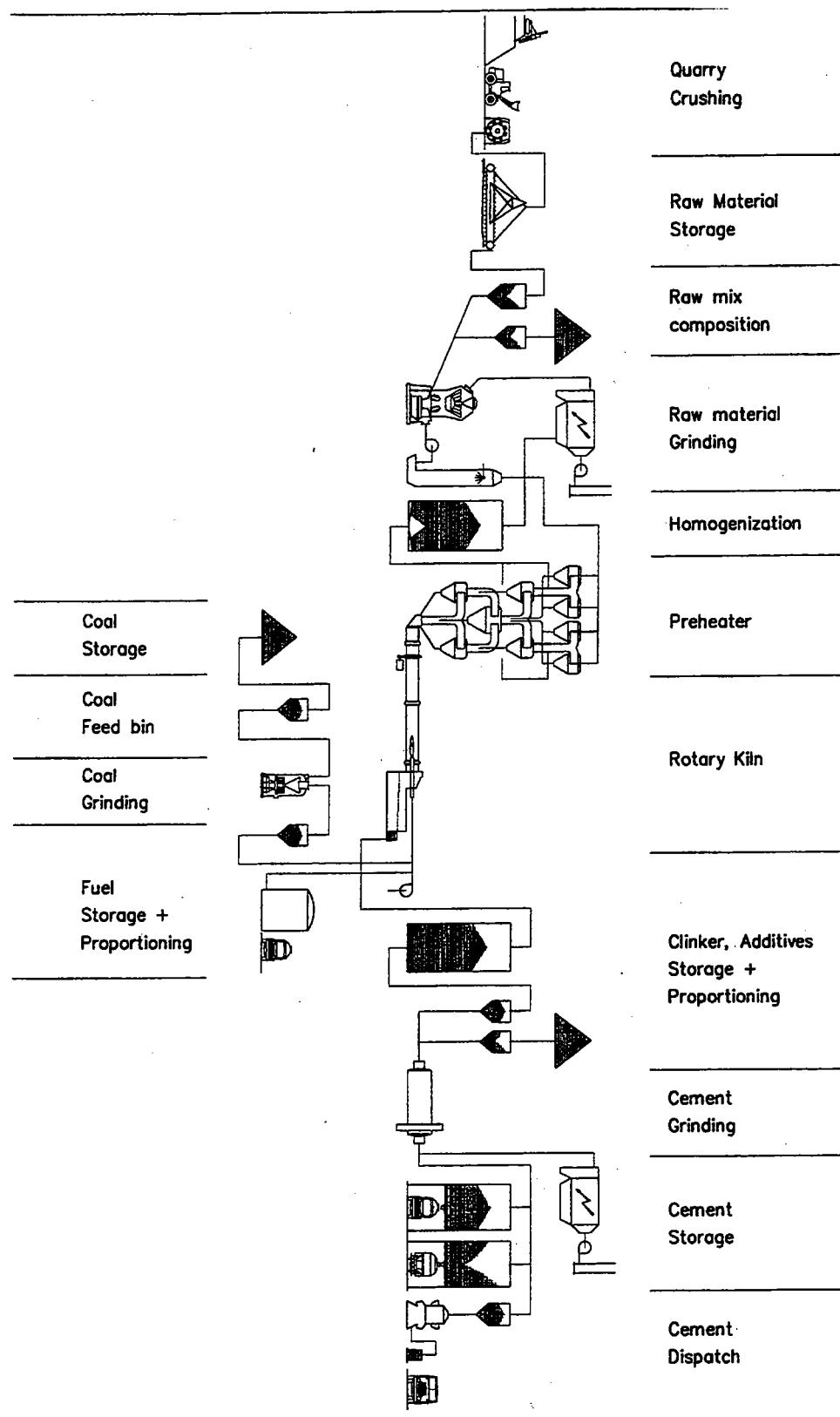
are common experience and very often accepted to be inevitable. The use of a sledge hammer and poke rods are well known but ineffective means to compensate for the adverse consequences of a careless and incompetent bin design.

It has to be mentioned that the attitude of the cement industry's towards bin design has changed fundamentally in the past fifteen years. Modern test procedures (as the shear test) and design concepts (mass-flow) are no longer ignored but accepted.

In this paper an attempt is made to give a survey on 'bulk solid storage in bins'. The following topics will be dealt with:

- ◆ description of the different bin design concepts and the resulting flow patterns,
- ◆ description of the bulk solid characteristics which are relevant in bin design and their experimental determination,
- ◆ analysis for product flow in bins,
- ◆ criteria for the design of bin/feeder systems,
- ◆ possible measures for improving the flow pattern for existing bins.

**Figure 1 Cement Process Flow Sheet**



## **2. BIN DESIGN CONCEPTS**

The flow pattern that develops in bins as the stored bulk product discharges under gravity is commonly demonstrated by means of transparent bins filled with layers of differently colored product. Such a set-up allows to observe the changes in stratification during flow, helped to give an insight to the nature of gravity flow of free-flowing and cohesive bulk products and allowed to understand the influence of wall inclination and outlet size on the flow pattern. It became evident the flow pattern can be classified into two

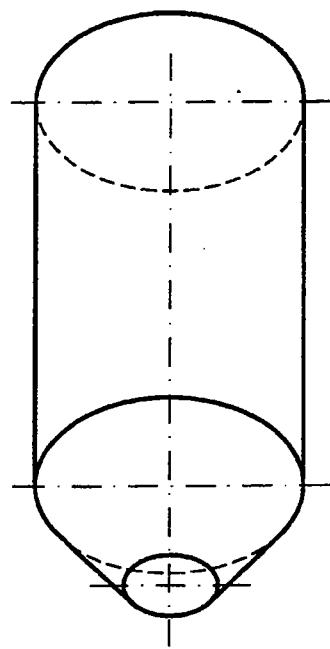
- ◆ funnel-flow, and
- ◆ mass-flow.

### **2.1 The Funnel-Flow Concept**

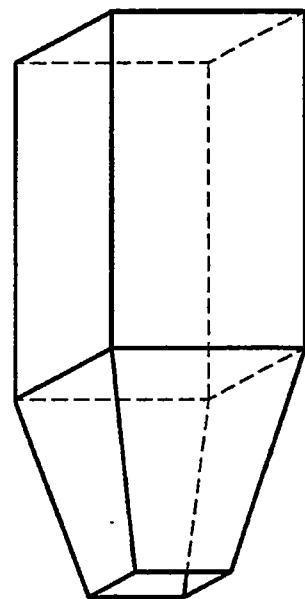
#### **2.1.1 Bin Shapes**

The funnel-flow bin type is the bin type with still the widest application in cement industry. Such bins may either be flat-bottomed or equipped with discharge hoppers. In case of the latter the flat hopper wall inclinations are the typical bin characteristic. Typical funnel-flow type bin shapes are shown in Fig 3.

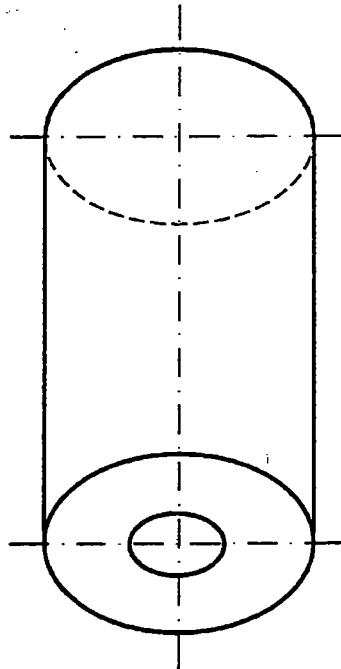
**Figure 3**      **Funnel-Flow typical bin shapes**



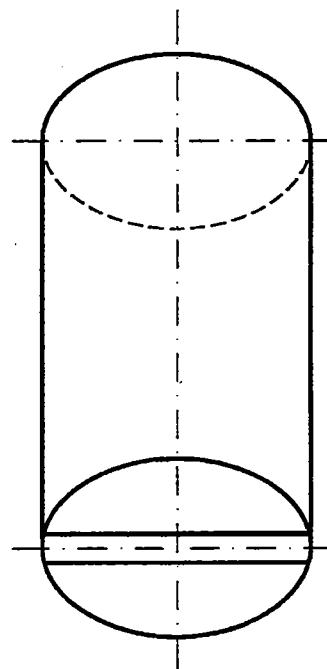
**conical hopper  
circular outlet**



**pyramid hopper  
square outlet**



**flat-bottomed  
circular outlet**



**flat-bottomed  
slot outlet**

### 2.1.2 Flow Pattern

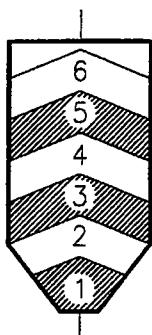
When filling a bin, product will always segregate: The coarse grains will roll down the slope of the surface pile to the bin's circumference while the fines will predominantly be accumulated in the bin's center. (Fig 4.1)

Development of the flow pattern in funnel-flow type bins depends on the product's flow characteristics, the relation of feed rate versus discharge rate and the arrangement of the feed relative to the discharge opening. When opening the outlet of a funnel-flow type bin, product will flow in a narrow core only that forms just above the bin's outlet while the surrounding product remains at rest. Bulk solid discharge is essentially irregular regarding rate and density. Funnel-flow type bins can typically not be emptied completely what results in a reduced live capacity. The discharge order is inverted compared to the loading order, i.e. the bin shows a first-in last-out flow sequence.

- ◆ For *no feed conditions* (Fig. 4.2) the product that will be discharged first is the fine product from the bin center zone. Product surface will then be inverted from a pile to a funnel shape, product level in the bin will fall. With the coarse particles from the bin's circumference now rolling down the slope to the center, granulometry of the discharged product changes from fine to coarse. All the product surrounding the center core remains at rest. The discharge order is inverted compared to the loading order, i.e. the bin shows a first-in last-out flow sequence.
- ◆ In case the *feed rate is larger than the discharge rate* (Fig. 4.3) product level in the bin is rising, the product surface keeps a pile shape and the product's fine portion is predominately discharged as all the coarse particles roll down the pile slope. All the product surrounding the center core remains at rest.
- ◆ In cases that *feed rate and discharge rate are similar* (Fig. 4.4) product level in the bin and shape of product surface will remain constant. Product do not segregate on feeding as it passes directly to the bin outlet via the activated center core. Again all the product surrounding the center core remains at rest.

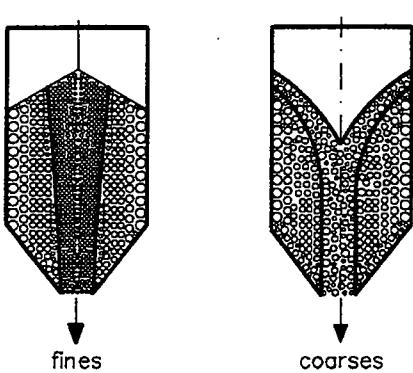
**Figure 4** Flow sequence in funnel-flow type bins

**FIG. 4.1** Feed no discharge



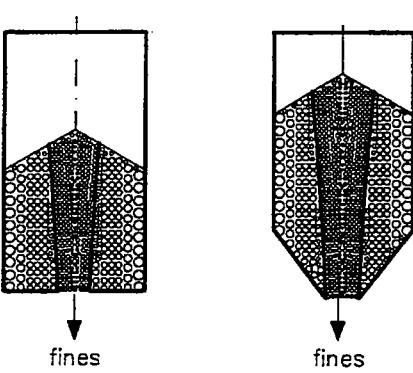
- product segregation

**FIG. 4.2** Discharge no feed



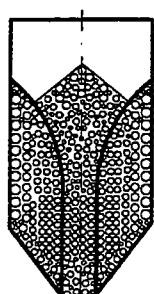
- falling product level
- preferred discharge of coarse fraction

**FIG. 4.3** Discharge rate  $\ll$  Feed rate



- rising product level
- preferred discharge of fine fraction

**FIG. 4.4** Discharge rate = Feed rate



- constant product level
- no segregation

### 2.1.3 Operation Problems (Fig. 5)

#### *Erratic flow and Flushing*

Bulk solids do not flow consistently in vertical or very steep channels and have a tendency to form voids topped by product arches. As such an arch breaks, the product falls into a void. Coarse product tends to pack under the impact on the feeder and to form another arch again, discharge rate will be erratic. Fine powders will get aerated when falling into the void and may then behave as a liquid flushing the feeder.

#### *Interrupted Flow: Arching and Rat-holing*

Funnel-flow type bins are subject to arching and rat-holing. Product discharge may be interrupted when product consolidation in the bin is that important that formation of a stable cohesive arch or rat-hole becomes possible.

#### *Product degradation*

Product may degrade due to segregation or excessive storage at rest.

Product segregation when filling bins can not be avoided. The funnel-flow sequence do not correct the adverse effect of segregation.

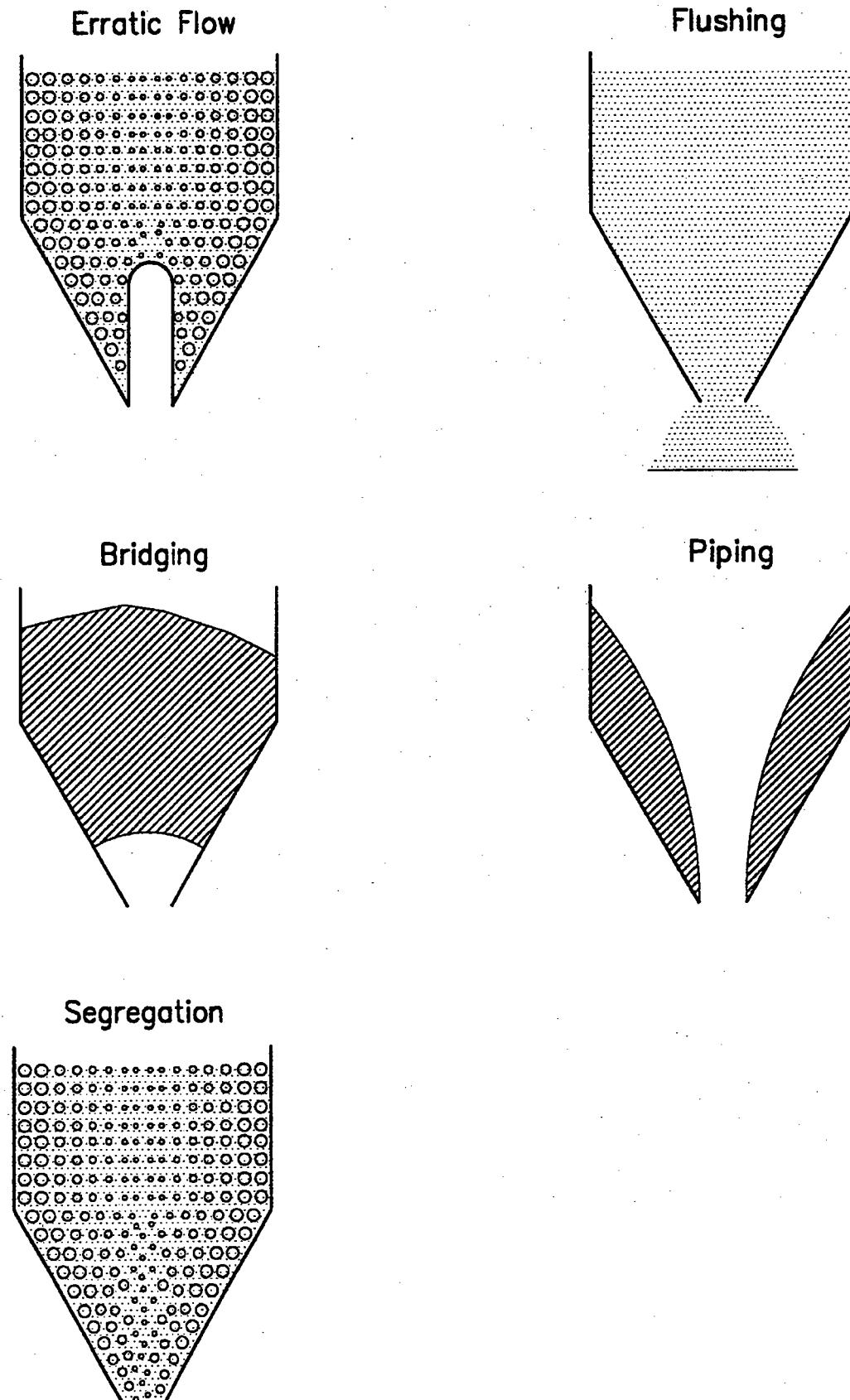
Extensive storage at rest of the product in a bin's dead zones may result

- ◆ in lump formation with the possibility that such lumps plug later the bin outlet,
- ◆ in hang-ups on the bin walls,
- ◆ in a loss of bin live capacity due to incomplete emptying.

### 2.1.4 Evaluation of the Funnel-Flow Concept

- + maximized storage volume for a given headroom but only in case the bin volume may be cleared completely on a batchwise basis
- + low investment per  $m^3$  storage volume
- tends to erratic flow and an inconsistent discharge rate (inconsistent regarding flow rate and bulk density)
- first-in last-out flow sequence
- varying product quality at bin discharge as product segregation on feeding is not corrected
- non-flowing zones favoring product degradation with time resulting in spoiling, lump formation, wall hang-ups and loss of live capacity due to incomplete emptying
- subject to flow stoppages if the product consolidates (packs) sufficiently to form stable arches or rat-holes
- *Funnel-flow may be acceptable in cases*
  - where segregation is unimportant,
  - where product degradation is not likely to be a problem,
  - where feed rate consistency is not of prime importance

**Figure 5 Operation problems with funnel-flow type bins**



## **2.2 The Mass-Flow Concept**

### **2.2.1 Bin Shapes**

Typical characteristics of mass-flow bins are a slender shape, steep wall slopes of the discharge hopper and relatively large outlets. Typical mass-flow type bin shapes are shown in Fig 6.

### **2.2.2 Flow Pattern**

Product segregation when filling a mass-flow type bin can not be prevented with the coarse grains rolling down the piles slope to the bin circumference while the fines will predominately be accumulated in the bin center.

The flow pattern that develops in a mass-flow type bin differs from that of a funnel-flow type bin considerably. In mass-flow type bins all the stored product is activated and moves towards the bin outlet whenever product is discharged. This results in a first-in first-out flow pattern (Fig. 7). Mass-flow type bins can typically be emptied completely at uniform discharge rate.

### **2.2.3 Operation Problems**

#### *Consistency of Product Discharge*

Product discharge out of mass-flow type bins is consistent in rate and bulk density thus not problematic.

#### *Interrupted Flow: Arching*

A mass-flow type bin only loses its beneficial properties in case the outlet is insufficiently sized or the outlet is not fully effective. In such cases arching and rat-holing become possible with the flow pattern changing to funnel-flow.

#### *Product degradation*

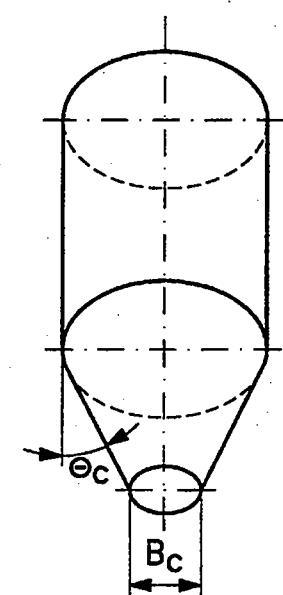
Zones of stagnant product will not form in mass-flow type bins at least as long as the bin outlet is fully active i.e. as long as all the stored product gets activated whenever any of it is reclaimed. The product sliding downwards along the bin walls keeps them clean and prevents formation of product lumps and wall hang-ups.

The discharge hopper acts as a mixer correcting product segregation that took place while filling the bin. This due to the fact that when emptying a mass-flow type bin the product surface keeps its shape down to the transition.

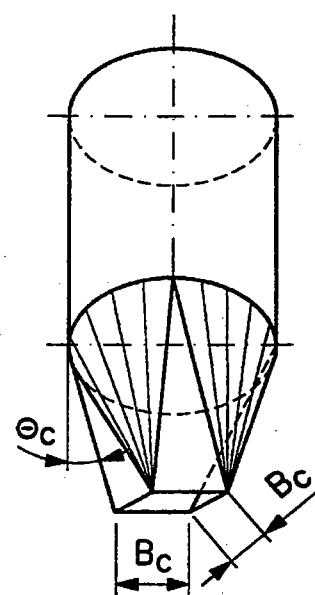
### **2.2.4 Evaluation of the Mass-Flow Concept**

- + product flow out of the bin is uniform independent of the head of product in the bin, erratic flow and flushing are absent
- + first-in first-out flow sequence preventing product deterioration due to excessive storage at rest periods
- + remixing effect for products which segregate on feeding
- + non-flowing zones are absent as are formation of product lumps and wall hang-ups
- limited storage volume for a given headroom
- high investment per  $m^3$  storage volume
- Mass-flow is the preferred flow pattern. Mass-flow type bins should always be selected in cases
  - where segregation is important,
  - where product degradation is a problem,
  - where feed rate consistency is of prime importance (e.g. for feed bins).

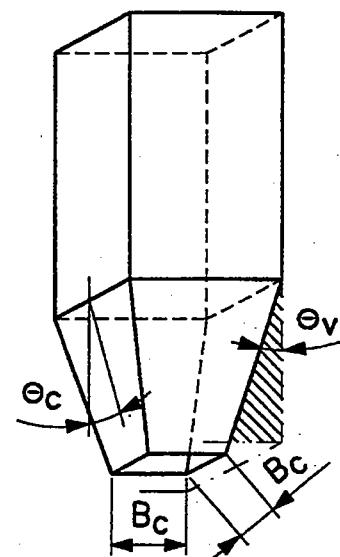
Figure 6 Mass-flow : typical bin shapes



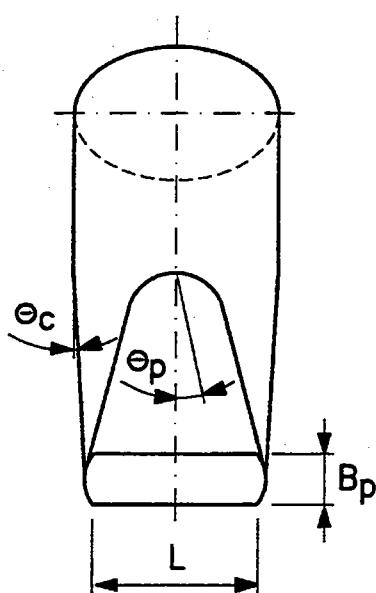
conical hopper  
circular outlet



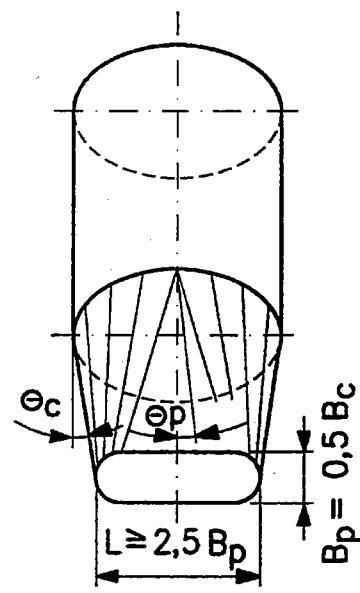
transition hopper  
square outlet



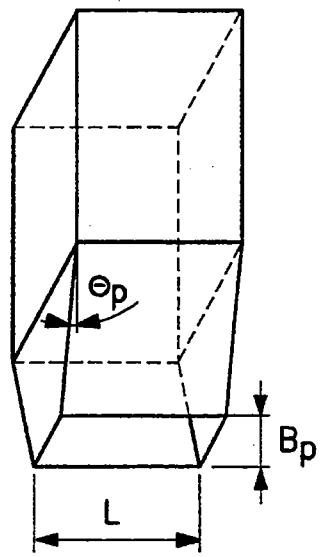
pyramid hopper  
square outlet



chisel hopper  
slot outlet



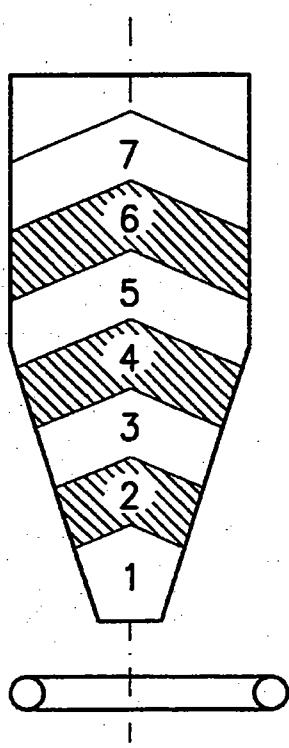
transition hopper  
slot outlet



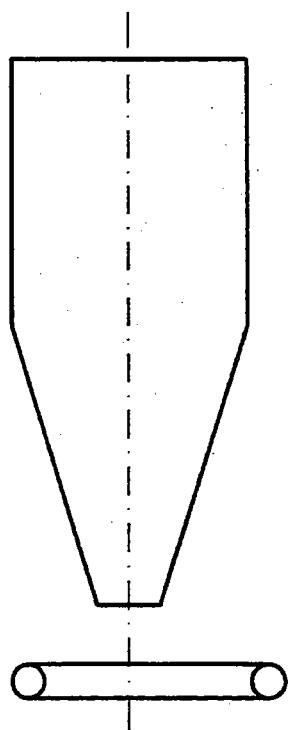
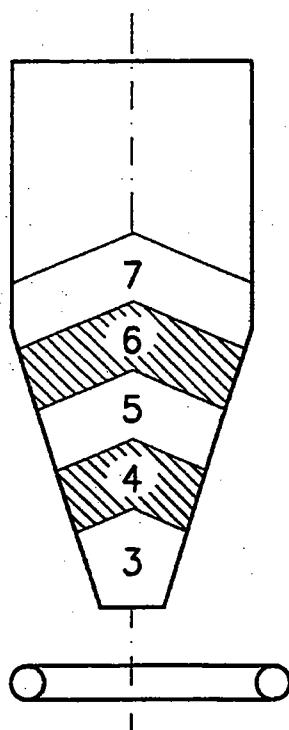
wedge type hopper  
slot outlet

**Figure 7 Flow sequence in mass-flow type bins**

**Feed**



**Discharge**



## **2.3 The Expanded Flow Concept**

### **2.3.1 Bin Shapes**

The typical shape of an expanded-flow type bin is shown in Fig. 9. From this figure the concept becomes evident: The selected bin discharge configuration is that of a composite hopper with the upper hopper section designed for funnel-flow and the lower section for mass-flow.

### **2.3.2 Flow Pattern**

It is evident that the expanded-flow concept combines both the funnel-flow and the mass-flow pattern. This is a creative way of increasing a bin's storage capacity while ensuring consistent product discharge.

### **2.3.3 Operation Problems**

#### *Consistency of Discharge Rate*

Product discharge out of expanded-flow type bins will be consistent in rate and density provided the lower hopper is properly sized for mass-flow.

#### *Interruption of flow: Arching and Rat-holing*

Arching and rat-holing will be absent with bins of the expanded flow type provided the lower hopper is properly sized for mass-flow.

#### *Product Degradation*

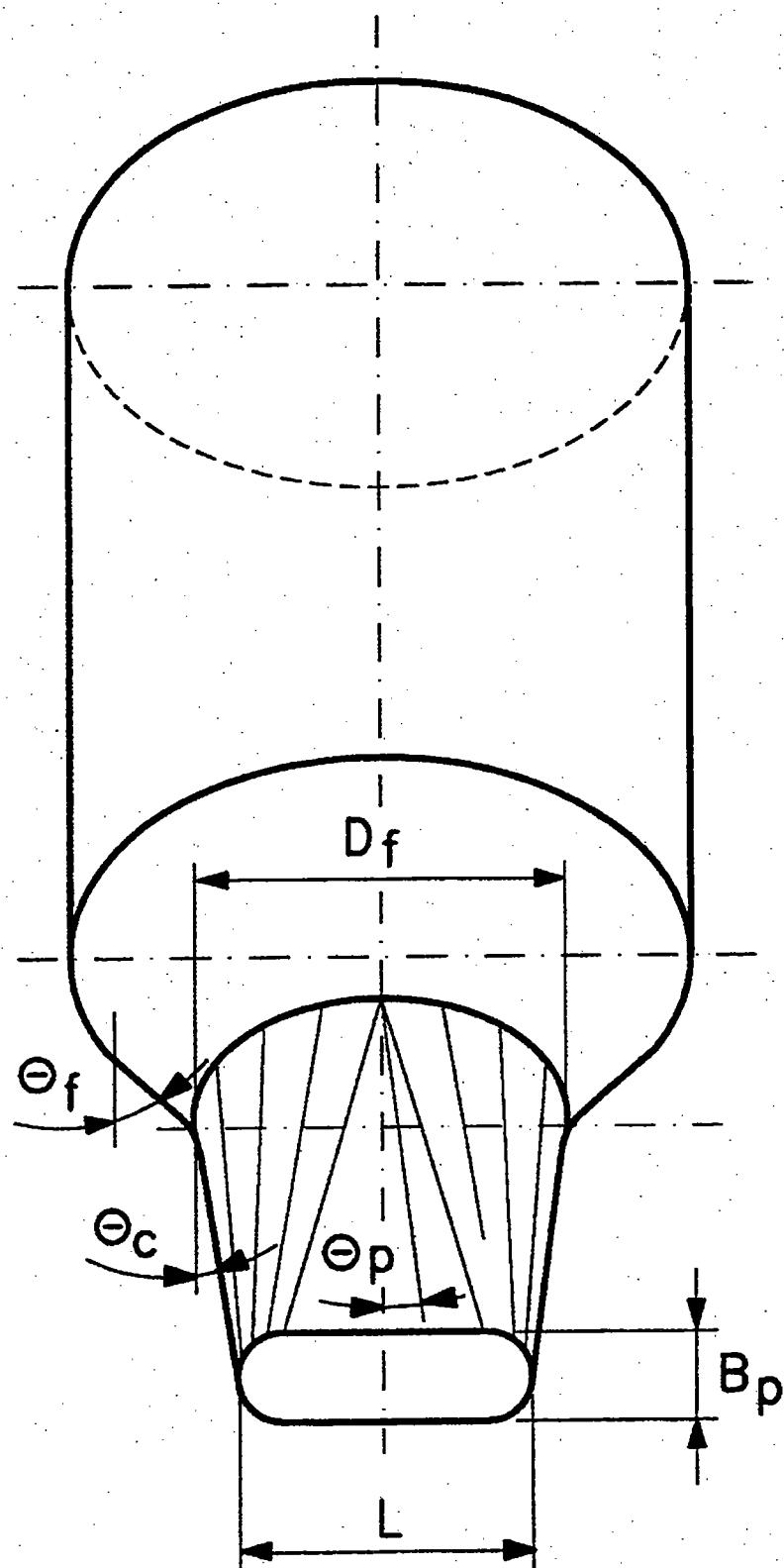
In an expanded-flow type bin's funnel-flow section a core of activated product will form but the surrounding product will remain at rest. With products that tend to consolidation (packing) expanded-flow type bins may not be cleared completely, the formation of product lumps and of wall hang-ups can not be excluded.

Segregation that took place while filling the bin can only partly be corrected flowing through the mass-flow hopper section.

### **2.3.4 Evaluation of the Expanded-Flow Concept**

- + optimized storage volume for a given headroom
- + relatively low investment per m<sup>3</sup> storage volume
- + product flow out of the bins is uniform
- + partial remixing effect for products which segregate on feeding
- last-in first-out flow sequence
- non-flowing zones favoring product degradation with time
- *Expanded-flow may be useful*
  - *where segregation is unimportant,*
  - *where product degradation is not likely to be a problem,*
  - *as a means to improve the insufficient flow pattern of a given bin.*

Figure 9 Expanded-Flow : typical bin shape



### **3. THE NATURE OF BULK SOLIDS**

#### **3.1 Introduction**

A bulk solid consists essentially of a multitude of granules (particles) which are randomly grouped to form of a bulk. These granules differ in size, in shape, in hardness, in surface texture, in chemical composition, etc.

The nature of a bulk solid not only depends on the characteristics of its constituent particles but also on factors as its way to compact and get strength (i.e. its cohesion), its angle of repose, its tendency to adhesion, its wall friction, the influence of moisture and storage at rest.

Hence it follows that any characterization of bulk solids must consider two levels

- ◆ the *features of the constituent particles*, and
- ◆ the *features describing a products bulk form*.

Unfortunately nowadays level of knowledge is still not sufficient as to allow for a reliable prediction of a bulk solids behavior based solely on the characteristics of its constituent particles.

A first step in the characterization of bulk solids is always a qualitative description of its behavior, of its ‘personality’. Questions to be asked are

- does it flow easily or is it sticky;
- is it fragile, abrasive, corrosive, explosive, etc.

Such descriptive terms are essential when communicating information on bulk solids. But they are unlikely sufficient as to allow for the design of handling systems which are matched to the product. For this purpose measurable numerical parameters are required which characterize a bulk solid in a quantitative manner. The most important of these parameters will be discussed in more detail in the following.

#### **3.2 Relevant Characteristics of Bulk Solids**

##### **3.2.1 Particle Size and Particle Size Distribution (Granulometry)**

Qualitative terms commonly used to describe the granulometry of a bulk solid are given in below table.

**Table: Descriptive terms for bulk solid granulometry**

<b>Descriptive term</b>	<b>Particle Size Range</b>	<b>Example</b>
coarse (crushed) solid	5-300 mm	limestone
granular solid	0.3 - 5 mm	sand
particulate solid:		
- coarse powder	100 - 300 $\mu\text{m}$	separator grits
- fine powder	10 - 100 $\mu\text{m}$	cement
- superfine powder	1 - 10 $\mu\text{m}$	dust collector product
- ultrafine powder	< 1 $\mu\text{m}$	paint pigments

Above qualitative terms are not sufficiently precise for the description of conglomerates of irregularly shaped and sized particles. Quantitative parameters are required for the description of particle size, size distribution and shape.

*Monosized spherical particles* are easy to be described. One single dimension is required, the particle diameter.

For a *conglomerate of spherical particles* of varying sizes the situation is more complex. For the characterization of particle size distribution the definition of an average particle diameter is required together with some information on particle size distribution.

The situation gets worse in case of *industrial, non-spherical bulk solids*. The parameters used for the description of particle size, size distribution and shape need careful definition. It is common industrial practice to determine the *granulometry* of bulk solids by using one of the sizing techniques given in below table. Selection of the sizing technique depends on the product's particle size range.

**Table: Sizing techniques and useful range**

<b>Sizing Technique</b>	<b>Useful Range</b>
• dry sieve analysis	50 µm - 100 mm
• wet sieve analysis	10 µm - 100 mm
• particle sedimentation	2 µm - 75 µm
• laser granulometry	1 µm - 600 µm

The results of a sieving test can easily be represented in a *histogram* (Fig. 10.1), i.e. by drawing rectangles over the selected class intervals. The area of each rectangle is proportional to the percentage of particles in that class. A smooth curve through the intervals results in a grain size distribution curve.

An even more useful way for the representation of the analysis data is the *cumulative graph* (Fig. 10.2). In such a graph the particle size is represented along the horizontal axis whereas the cumulative percentage retained or passing is given on the vertical axis. The advantage of this representation is that grain sizes not determined experimentally are reliably predicted as is the *median particle size* (the 50% size).

The median particle size mentioned above is probably the most common term used for representing a bulk solids average particle size. But it has to be noted that there are other definitions for an equivalent diameter such as the mean volume diameter or the mean surface diameter.

$$\begin{aligned} \text{◆ mean volume diameter} \quad d_{pm} &= \left( \frac{6V_{pm}}{\pi} \right)^{\frac{1}{3}} = \left( \frac{1}{N} \sum d_v^3 \right)^{\frac{1}{3}} \\ \text{◆ mean surface diameter} \quad d_{sm} &= \left( \frac{A_{spm}}{\pi} \right)^{\frac{1}{2}} = \left( \frac{1}{N} \sum d_s^2 \right)^{\frac{1}{2}} \end{aligned}$$

Which of above figure is used for characterization of a bulk solid's granulometry depends on the product's industrial use. The median is common in cement industry for characterization of e.g. raw meal and cements, whereas the mean surface diameter is relevant in chemical industry for the characterization of e.g. catalysts.

### 3.2.2 Particle Shape

The shape of the particles of a bulk solid has proven to be relevant for its packing and flow behavior. But establishing quantitative data on particle shape is discouraging as there is hardly an agreement on how to define shape factors. This above all as defining the shape of non-spherical particles in mathematical terms is not easy.

For the time being the effect of particle shape on a bulk solid's flow behavior can only be based on qualitative observations:

- ◆ a fibrous appearance may warn of a tendency to particles interlocking,
- ◆ a sharp angular particle shape may indicate that abrasive wear may be excessive.

Figure 10 Graphical methods of presenting particle size distribution

FIG. 10.1 The Histogram

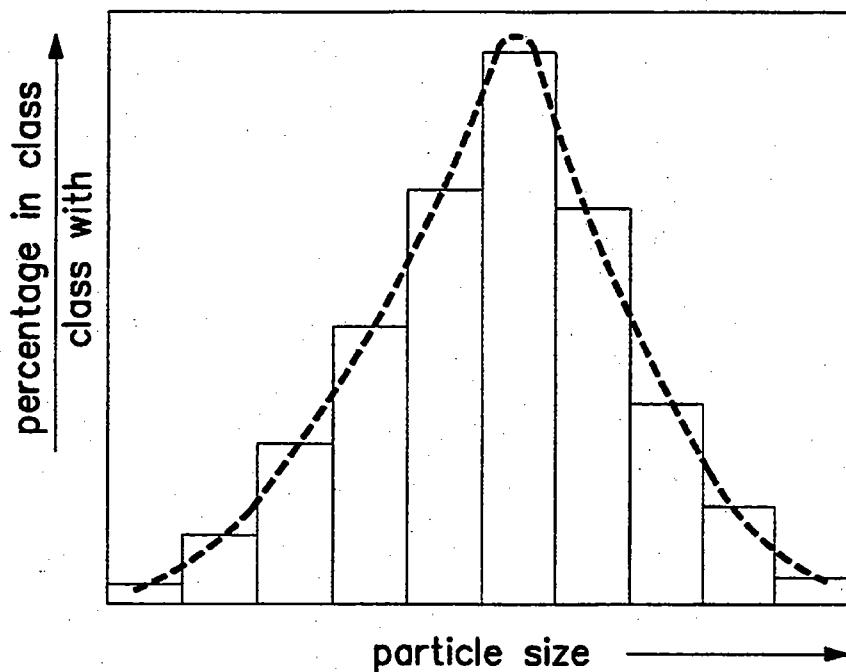
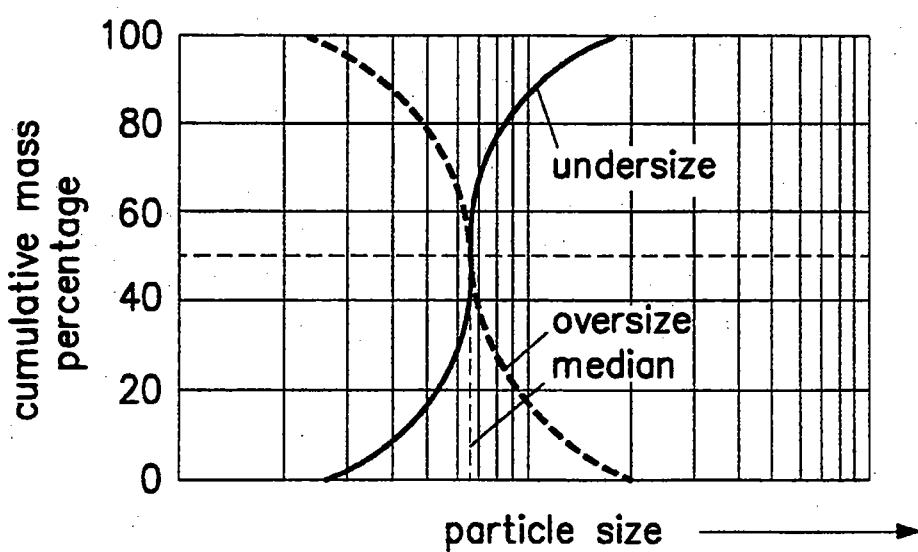


FIG. 10.2 The cumulative percentage graph



### 3.2.3 Particle Hardness

Knowledge regarding the hardness of the particles constituting a bulk solid is important in that respect that it gives an indication regarding the product's abrasivity. It is common experience that a product is the more abrasive the harder its particles are.

F. Mohs proposed already in 1822 a scale of hardness based on ten standard minerals grouped according a simple scratch test.

**Table: Mohs scale of hardness**

Mohs scale hardness	Material	Chemical formula	Scratch test
1	Talc	$Mg_3(OH)_2 \cdot (Si_2O_5)_2$	Very soft, can be powdered with fingers
2	Gypsum	$CaSO_4 \cdot 2H_2O$	Moderately soft, can scratch lead
3	Calcite	$CaCO_3$	can scratch finger nail
4	Fluorite	$CaF_2$	can scratch a copper coin
5	Apatite	$Ca_5(PO_4)_3(Cl, F)$	can scratch a knife blade with difficulty
6	Feldspar	$KAlSi_3O_8$	can scratch a knife blade
7	Quartz	$SiO_2$	all products harder than 6 will scratch window glass
8	Topaz	$Al_2F_2SiO_4$	
9	Corundum	$Al_2O_3$	
10	Diamond	C	

The Mohs scale proved to be too coarse and insufficiently reproducible. This resulted in the introduction of a number of *indentation tests* above all for metals. The most common hardness figures are

- ◆ the Vickers Pyramid Number VPN,
- ◆ the Brinell Hardness Number BHN,
- ◆ the Rockwell hardness HRC.

There is sufficient knowledge available as to allow for relating the different hardness numbers to the Mohs scale.

### 3.2.4 Voidage and Bulk Density

Bulk solids are constituted by a bulk of randomly packed particles which differ in size and shape. Bulk solids are thus combinations of particles and void space. The percentage of the volume not occupied by particles is referred to as the *voidage*.

$$\text{voidage, } \varepsilon = \frac{V_{\text{voids}}}{V_{\text{particles}} + V_{\text{voids}}} \times 100[\%]$$

Note that sometimes the term *porosity* is applied with bulk solids as a synonym for voidage. However, it is advisable to reserve this term for the description of the structure of individual particles.

A quantity of a bulk solids has an apparent density, usually called *bulk density*, which is defined to be the mass of material divided by the bulk volume.

$$\text{bulk density, } \rho_b = \frac{m_{\text{solid}} + m_{\text{voids}}}{V_{\text{solid}} + V_{\text{voids}}} [t/m^3]$$

Writing  $\rho_p$  the particle density and  $\rho_f$  as the density of the fluid in the voids it follows another expression for the bulk density:

$$\text{bulk density, } \rho_b = (\sigma_p - \rho_f)(1 - \varepsilon) + \rho_f [t/m^3]$$

It is important to make a clear distinction between bulk density and particle density. For a single particle the density is defined as its mass divided by its volume. Thus, determination of a particle's density involves the measurement its mass and the volume occupied. For large particles the density can easily be determined by measuring the volume of liquid being displaced in a measuring cylinder.

Determination of a product's bulk density is more tricky. For coarse products, again the liquid displacement method can be used whereas for powders the use of a specific-gravity bottle or of an air-compression pycnometer is required.

### 3.2.5 Angle of repose

A bulk solid's angle of repose is defined to be the angle of an exhibited sloping product surface which forms e.g. when a product is piled or after slippage from a product pile. Quantitative determination of the angle of repose is discouraging in that respect that no unequivocal method is available. One has to accept that for the same product as many different angles of repose may be measured as measuring methods are used. Some of these methods are illustrated in Fig. 12 .

Besides the test procedure adopted and the skill of the operator the angle of repose depends upon the nature and condition of the bulk solid concerned (moisture, granulometry, electrostatic charging, storage at rest period).

Below table gives a qualitative evaluation of bulk solid flowability based on the angle of repose.

<b>Angle of repose</b>	<b>Flow behavior</b>
20 - 30 deg	free flowing
30 - 38 deg	easy flowing
38 - 45 deg	fair flowing
45 - 55 deg	cohesive
> 55 deg	very cohesive

The angle of repose should not be abused as a quantitative guide in bin design. But it may be a useful indicator for the contours of product storage piles, the cross-sectional area of a product bed on a belt conveyor, etc.

### 3.2.6 Cohesion and Adhesion

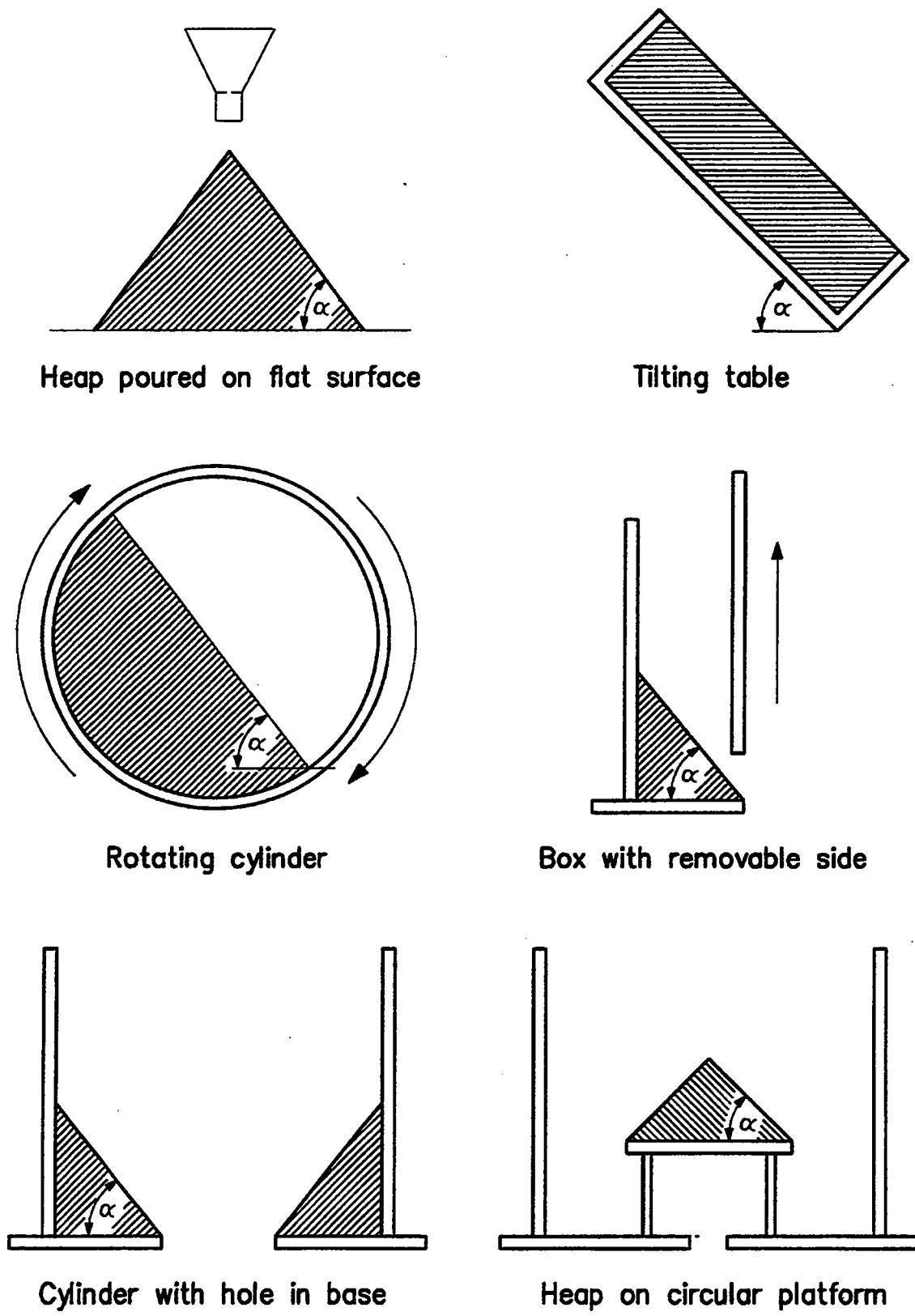
Flowability of a bulk solid is function of the forces of attraction or the 'cohesion' between its constituent particles.

In case the interparticle forces are low the bulk solid will easily flow with the single particles moving as individuals relative to one another. Dry sand or clinker are familiar examples from cement industry.

Interparticle cohesive forces are typically caused by moisture and electrostatic charging. The effect of such forces is especially pronounced with products containing a considerable portion of fines. Familiar examples for cohesive products in the cement industry are clay, natural and synthetic gypsum, fine coal, fly-ashes, etc. When cohesion is defined to be a bulk solid's resistance to shear under a given compressive (normal) stress quantitative measurement becomes possible. For details see paragraph 'Shear Strength'.

Flowability of bulk solids is not only concerned with cohesion but also with 'adhesion' on boundary surfaces such as the walls of a bin discharge hopper, the bottom and side surfaces of transfer chutes, etc. Whereas cohesion reflects the effects of interparticle attractive forces, adhesion describes a bulk solids tendency to stick on a boundary surface. The adhesions between a bulk solid and a type of surface material can quantitatively be measured using a test similar to the shear test mentioned above for cohesion. For details see paragraphs 'Shear Strength' and 'Wall Friction'.

**Figure 12 Methods of measurement of angle of repose**



### 3.2.7 Shear Strength

As with continuous material, the application of any force to a bulk solid tends to cause a shear deformation and will result in an opposing resistive force. With increasing magnitude of the applied force, a point will be reached where the bulk solid begins to deform with the constituent particles sliding relative to another.

For illustration let's consider the following simple experiment (Fig. 13) :

- ◆ Prepare a bulk solid specimen in a cylindrical mold (cross section A) by compacting the product applying a defined normal load  $F_N$ . The cylinder wall is assumed to be free of friction.
- ◆ Remove the cylindrical mold.
- ◆ Expose the specimen exposed to an increasing normal load (e.g. by filling a bottle of water). At a distinct load level which is termed *shear or product strength*  $F_C$ , the specimen will collapse and shear. The shear strength is determined just by weighing the bottle.

From this simple experiment it follows the existence of a *flow limit*. This flow limit is specific for each bulk solid and function mainly of the magnitude of the applied consolidating force. But it is also affected by factors as the particles nature (as e.g. their shape and packing arrangement), moisture content, thus the pre-history of the product.

Product strength can (unfortunately) not be determined directly with sufficient accuracy using above described simple experimental concept but rather needs to be derived from the results of so called shear tests. The concept of shear testing is to make specimens of a bulk solid shear under varying normal loads while measuring the appearing shear forces.

The result of such a test is commonly represented as a so called *yield locus* YL, i.e. as a plot of the shear strength  $S_f$  versus the compressive (normal) force  $F_N$ . A yield locus is thus a border line separating the range of stresses which cause no permanent deformation from the range of stresses causing failure and plastic flow.

Interpretation of a yield locus plot involves the use of Mohr circles of stress. From such a plot (Fig. 14) the following characteristics can be derived:

- ◆ drawing a Mohr circle tangential to a yield locus and passing through its end point gives the major principal stress  $\sigma_1$ , representing the initial state of sample consolidation;
- ◆ the Mohr circle drawn through the diagram's origin and tangential to a yield locus gives the unconfined yield stress  $\sigma_c$ , which represents a product strength at a free surface;

(Note that the unconfined yield stress for non-cohesive, free flowing bulk solids is equal to zero. Hence it follows that the yield locus representing such products pass through the diagram's origin!)

- ◆ the slope of the yield locus at any point defines the *dynamic angle of internal friction*  $\phi$ , which in practice is somewhat varying due to the typically slight curvature of the yield locus,
- ◆ the straight line tangential to the Mohr circle for the initial consolidating load and passing the diagram origin is termed the *effective yield locus* with its slope defining the *effective angle of internal friction*  $\phi_e$ .

Figure 13 Testing a bulk solid for flow

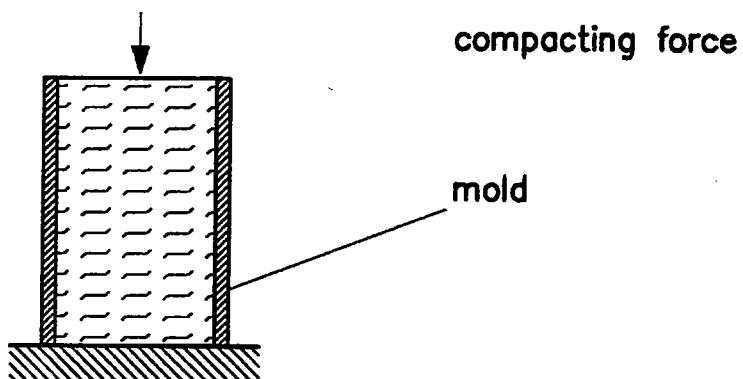


FIG. 13.1 Preparation of specimen

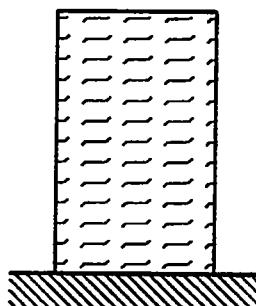


FIG. 13.2 Remove mold

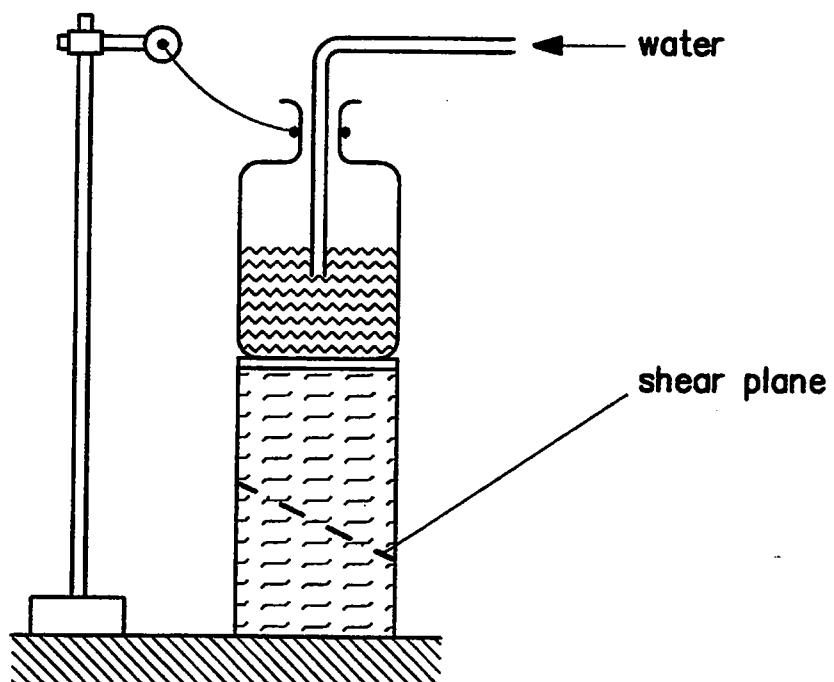
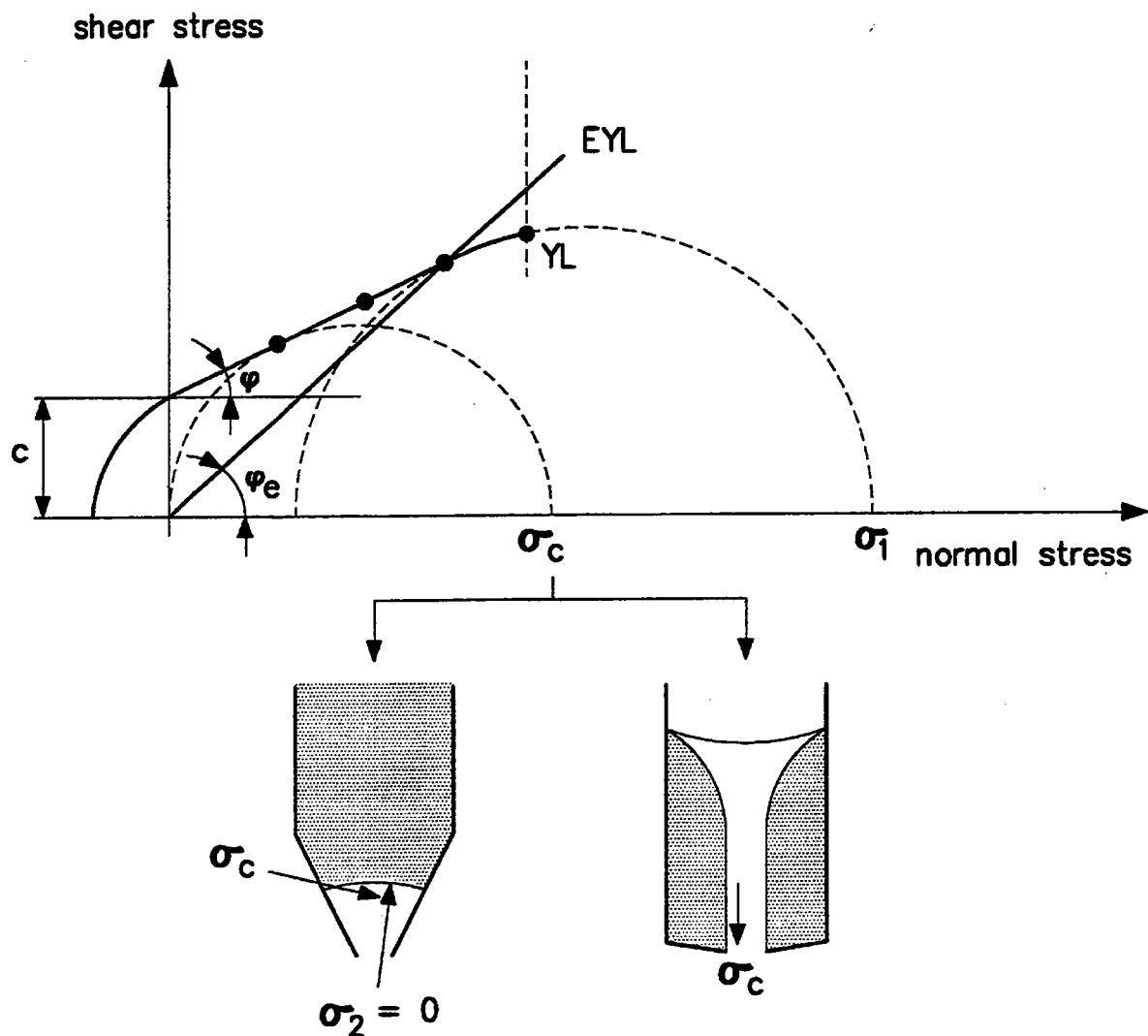


FIG. 13.3 Shear test

Figure 14 The yield locus



- YL measured yield locus
- EYL effective yield locus
- $\sigma_1$  major compressive stress representing the samples state of consolidation
- $\sigma_c$  unconfined yield stress representing product strength
- $\varphi$  dynamic angle of internal friction
- $\varphi_e$  effective angle of internal friction
- c cohesion

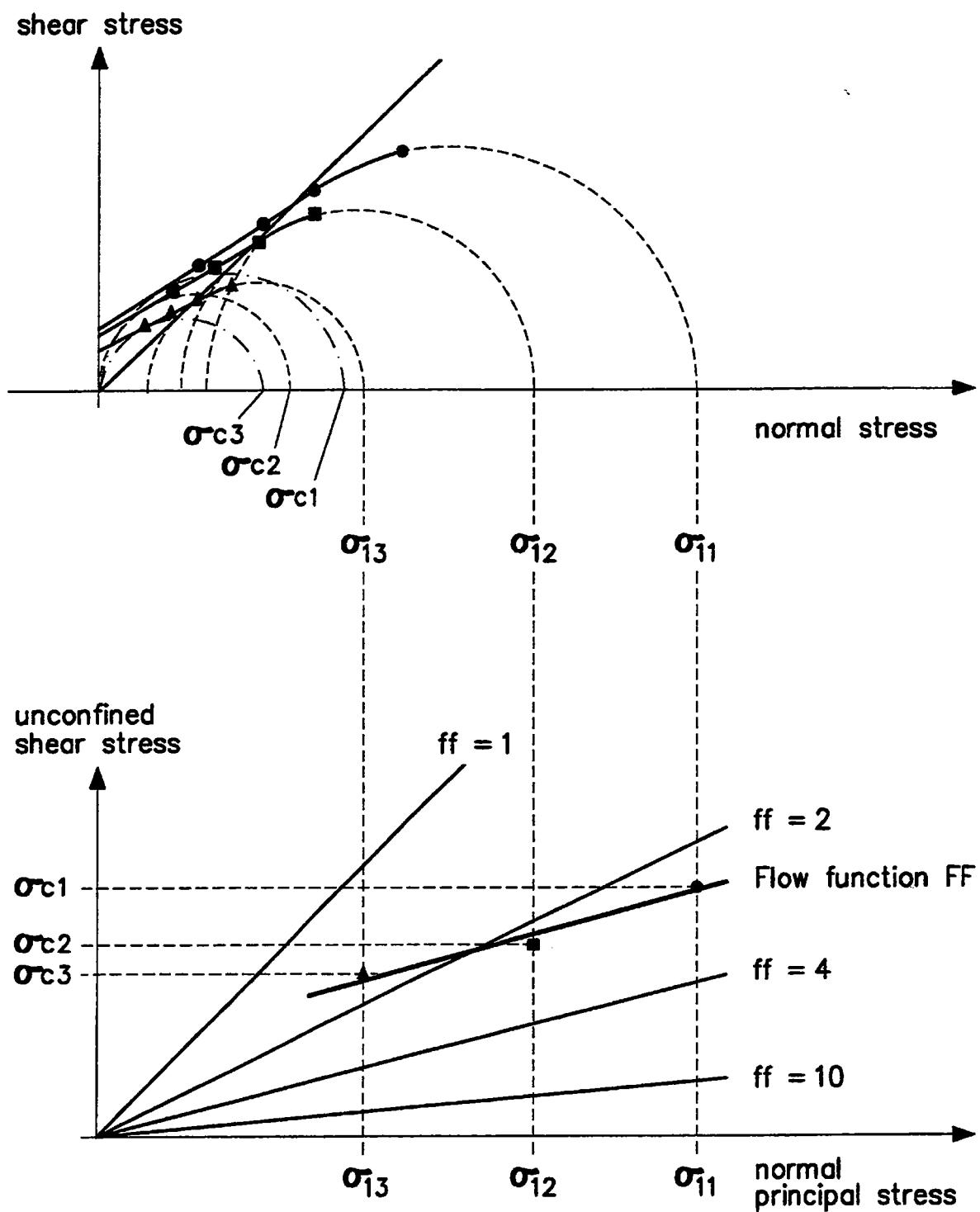
It has already been mentioned that a bulk solid's shear strength is affected by its state of consolidation as well as its pre-history. As a consequence a single yield locus is not a sufficient characteristic to describe a bulk solid's flow behavior as it is for a Coulomb type solid. For a full investigation of its flow properties specimens must be tested for different levels of product consolidation, i.e. a *family of yield loci*  $YL_i$  (Fig. 15) must be produced.

As already mentioned the shear strength of bulk solid's may be determined by means of a shear-testers. More than one type of shear testers have been developed with probably the *Jenike translational shear tester* being the most familiar one. For any experimental arrangement designed for testing the flowability of bulk products it is a prerequisite that the complicated stress conditions can be simulated which are imposed on bulk products while being filled into bins, during storage at rest in bins and when being discharged from bins.

Jenike's experimental technique meets these requirements. The set-up of such a tester (Fig. 16) is very simple: Two rings of equal diameter form the shear cell. Samples of the product under investigation are poured into such cells, are precompacted to different degrees of consolidation and made shear under varying normal loads. It is important that a consistent procedure for sample preparation and testing is followed. Jenike's translational shear tester is subject to a number of limitations as its limitation to fine products or to a product's fine portion only ( $< 3$  mm), its limited translational displacement as well as the complicated testing procedure.

The *torsional shear tester* arrangement as it is used at HMC's laboratory (Fig. 17) allows for a simplified testing procedures as it allows for unlimited strain. With such equipment the torques required to make the specimens shear are measured. The respective shear stresses required for the representation of the yield loci  $YL_i$  can be calculated.

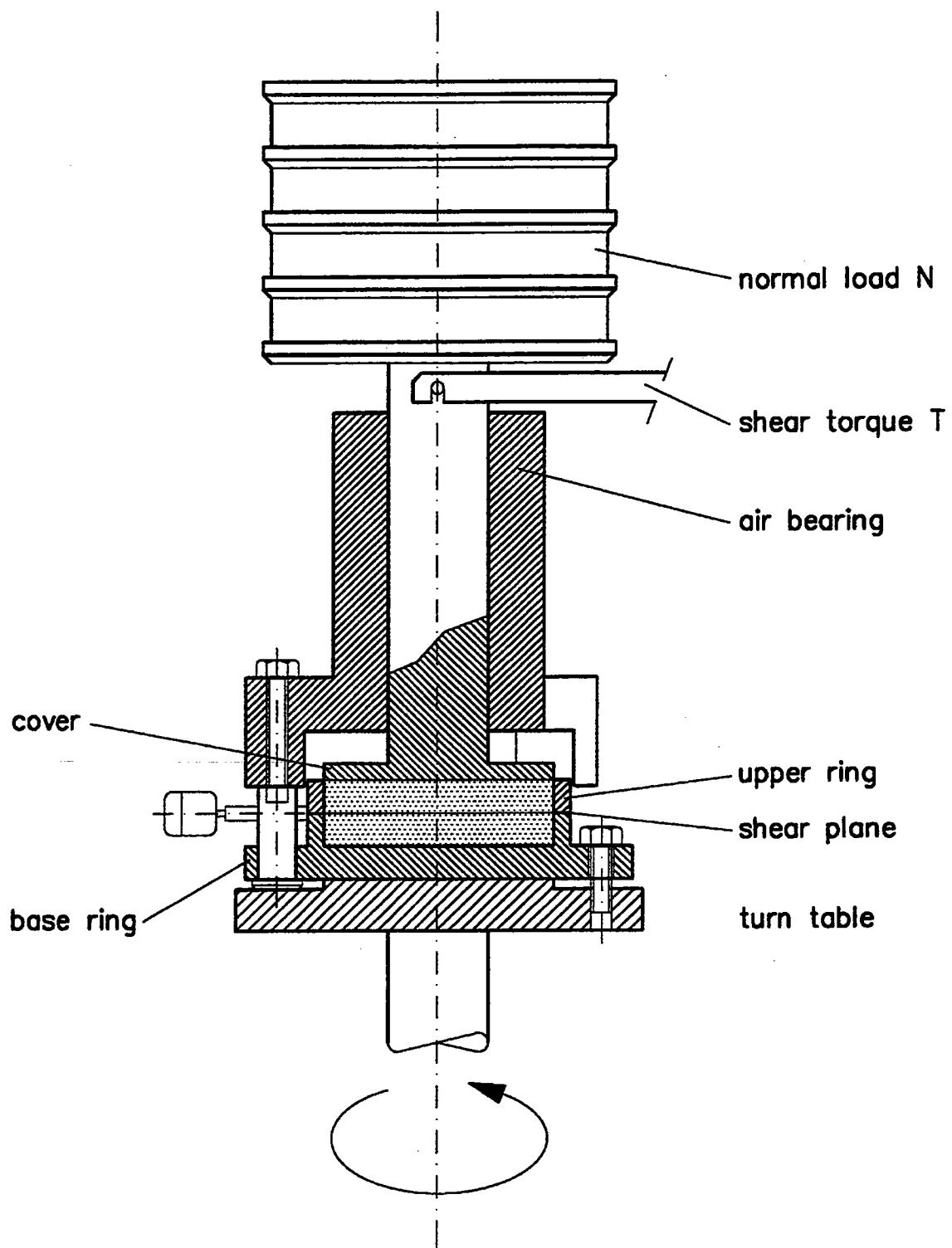
Figure 15 The flow function



**Figure 16 Shear test concepts**

	Rotational Shear Concept RO - 300	Translatory Shear Concept Jenike Shear Tester	
Arrangement for Testing the Internal Frictional Behaviour	<p>Rotational Shear Concept RO - 300</p>	<p>Translatory Shear Concept Jenike Shear Tester</p>	$N/N_x$ : Normal Compressive Load $S/S_x$ : Shear Force $T/T_x$ : Shear Torque
Arrangement for Testing the Wall Frictional Behaviour	<p>Arrangement for Testing the Wall Frictional Behaviour</p>	<p><math>N_x = \sigma_1 \cdot A</math></p>	<ol style="list-style-type: none"> <li>1 Base Ring</li> <li>2 Upper Ring</li> <li>3 Cover</li> <li>4 Sample of Bulk Solid</li> <li>5 Specimen of Wall Material</li> </ol>

Figure 17 The torsional shear tester



### 3.2.8 The Flow Function

A bulk solid's flow behavior is commonly characterized by its *Flow Function* which is defined as the ratio of consolidating principal stress versus product strength

$$FF = \frac{\sigma_1}{\sigma_c}$$

Hence it follows that a bulk solid is flowing the easier the higher its flow function is. The flow function allows for a rough evaluation of a product's flow behavior

FF < 1	non-flowing product
1 < FF < 2	very cohesive product
2 < FF < 4	cohesive product
4 < FF < 10	easy flowing product
10 < FF	free-flowing product

Above limits are represented in Fig. 15. Commonly the Flow Function and with it a bulk solid's flow behavior are function of the state of consolidation. In most cases the value for the Flow Function FF increases with increasing consolidating stress  $\sigma_1$ . Hence it follows that the flow behavior of various bulk solids may only be evaluated based on the Flow Function figures in case all measurements have been carried out on specimens prepared the same way (i.e. having the same state of consolidation).

### 3.2.9 Wall Friction

Bulk solid flow along a hopper wall or in a chute results in wall friction. Wall friction is function of the wall material characteristics (adhesion, smoothness of surface), the wall inclination, etc.

A linear model similar to that proposed for the internal friction of bulk solids can be used to represent the relationship between the normal force  $F_N$  pressing a particulate product against a constraining surface and the shear force  $S_w$  required to cause the product to slide along that surface

$$S_w = \mu_w F_n + C_w$$

where  $\mu_w$  is the coefficient of wall friction

$C_w$  is a coefficient defining the adhesion between bulk solid and containing surface

The line defined by above equation is termed *wall yield locus* WYL. For most bulk solids it is found below the yield locus YL and the angle of wall friction  $\phi_w$  being less than the angle of internal friction  $\phi$ .

To investigate a bulk product's frictional behavior on bin walls the shear testing concept is slightly modified. The lower ring of the shear cell is replaced by probes of possible bin wall materials. The testing procedure is the same as described above: The forces or the torques respectively which are required to make the sample shear under varying normal loads are measured. Again Wall Yield Loci (WYL<sub>i</sub>) can be produced when plotting the shear stresses versus the corresponding normal loads.

### **3.2.10 Moisture Content**

Product moisture can have a dramatic influence on a bulk solid's flow behavior in addition to cause effects such as chemical change, deterioration of quality, etc. Moisture analysis is therefore an important task in characterization of bulk solids.

A common expression for a bulk solid's moisture content is the percentage of water to wet solid:

$$\text{moisture content} = \frac{m_{H_2O}}{m_{\text{wet}}} \times 100 [\% H_2O]$$

It has to be noted that water presence in bulk solids may be in two different forms

- ◆ as *surface water* present on the surface of the particles only,
- ◆ as *inherent moisture* resulting from water being crystallized within the structure of the particles.

The most common method for determining a bulk solid's moisture content is still by determining the loss in weight for a product sample when drying it in an oven until its weight remains constant. The moisture content can then be calculated as

$$\text{moisture content} = \frac{m_{\text{wet}} - m_{\text{dry}}}{m_{\text{wet}}} \times 100 [\% H_2O]$$

When testing the surface moisture of bulk solids containing crystallized water in the structure of particles (e.g. gypsum, coal, etc.) the drying temperature must be selected that low that product dehydration do not occur.

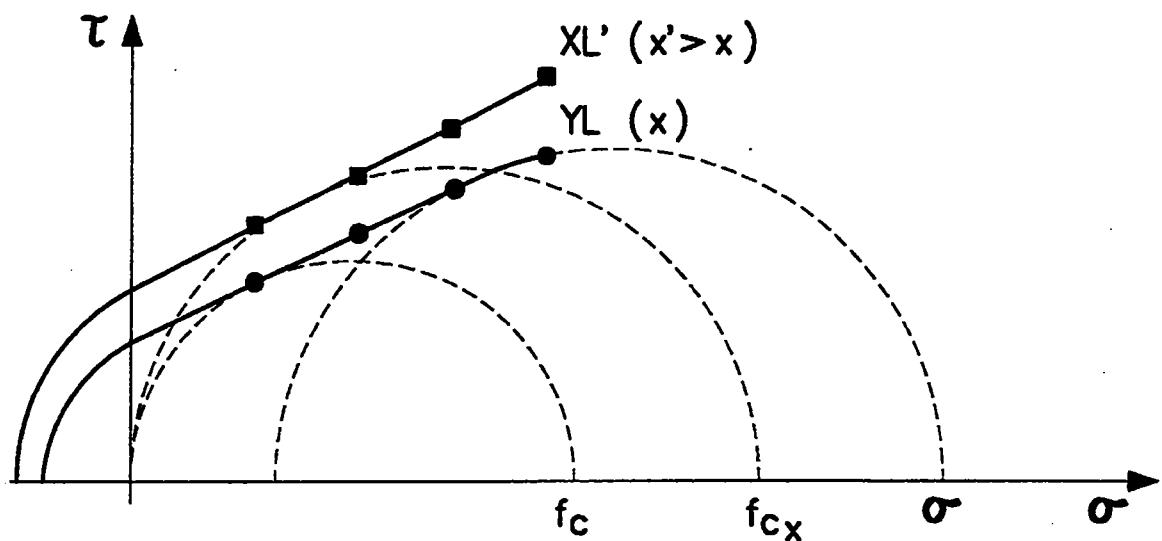
Recently faster analysis methods have been introduced for moisture determination such as infrared absorption, microwave absorption, nuclear magnetic resonance, ultrasonic, etc.

With regard to a bulk solid's flow behavior commonly two moisture limits can be observed

- ◆ a lower limit where flowability will deteriorate resulting in an increasing product strength, a reducing discharge rate, an increased tendency to arch, rat-hole and hang-up formation,
- ◆ an upper limit where the bulk solid is saturated (all voids filled) and flowability improves again.

The dramatic effect of moisture on a bulk solids flow behavior has already been mentioned. Testing the product strength at different moisture levels is considered an important task in bulk solid's characterization, i.e. that additional yield loci (Fig. 18) should be produced at the moisture levels observed in industrial live.

Figure 18 The influence of moisture on the flow behaviour of bulk solids



$x$  = moisture level

#### 4. DESIGN OF BIN/FEEDER SYSTEMS

##### 4.1 Analysis for Flow

###### 4.1.1 Theories

The theoretical work concerning the flow behavior of bulk solids in bins has been initiated by the already mentioned A.W. Jenike. He adapted theory and experimental technique of soil mechanics to the problem of bulk solid handling. He postulated that bulk solids behave similar as Coulomb solids. Their flow behavior is thus characterized by limiting stress envelopes, so called Yield Loci ( $YL_i$ ) which separate the range of stresses that will cause no permanent deformation from the range of stresses that will cause failure and plastic flow. The flow behavior of bulk solids depend on their pre-history, i.e. their consolidation, moisture take-up, storage at rest, etc. Hence it follows that the flowability of bulk solids can be characterized sufficiently by a family of yield loci only. This in contrast to Coulomb type solids for which a single yield locus is a sufficient characteristic.

Following Jenike's theory bin/feeder systems can be designed for consistent operation. Precondition is that the design prevents any formation of obstructions to flow.

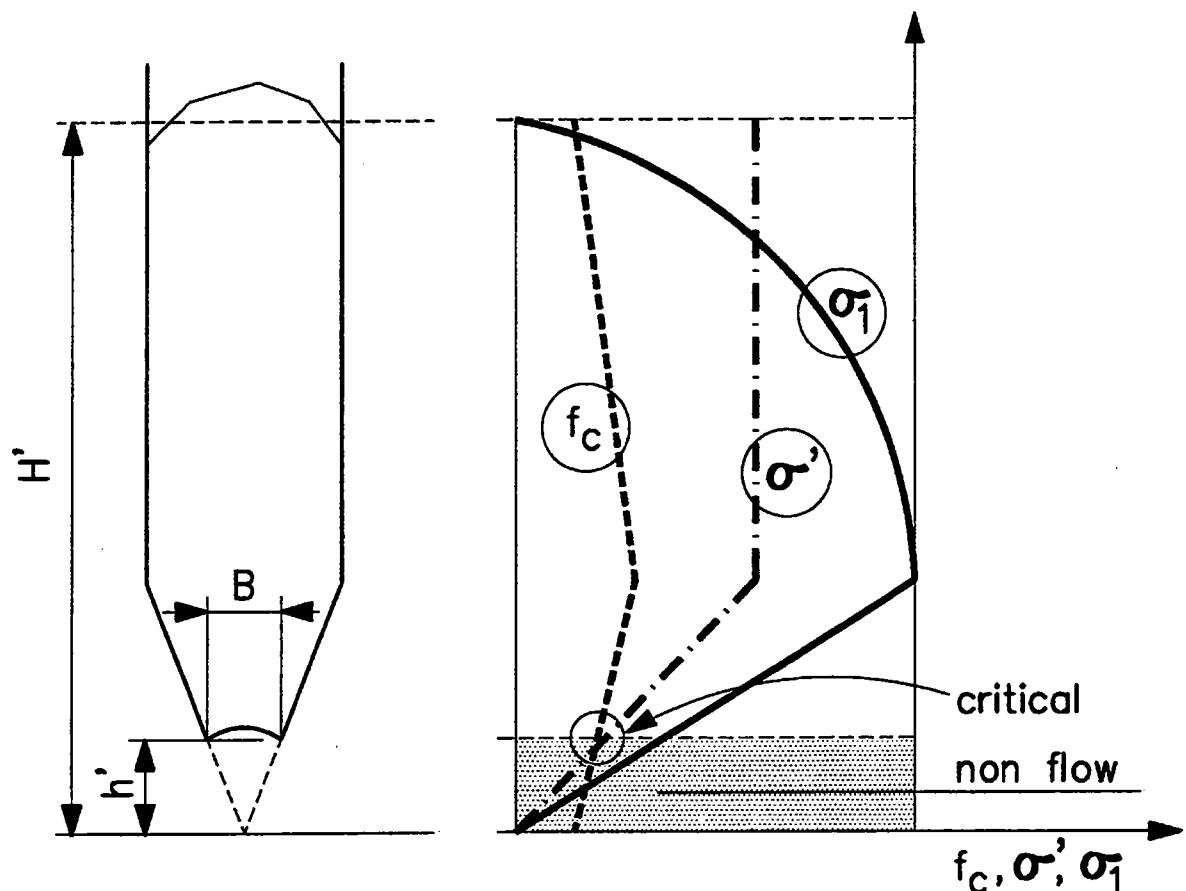
###### 4.1.2 The flow - no flow Criterion

Consider a mass-flow bin. The bulk solid is unconsolidated when it is fed into a bin but becomes consolidated with continuing filling, i.e. with increasing filling height. In the cylindrical bin section a *static or peaked stress field* develops with the consolidating stress  $\sigma_1$  varying from zero at the top surface towards a maximum near the transition to the converging hopper section. At this transition the stress field changes its orientation from peaked (static) to arched (dynamic). This results in an abrupt increase in stress level to a peak value. Below the transition in the bin discharge hopper the consolidating stress  $\sigma_1$  decreases within the prevailing *dynamic (arched) stress field* towards zero at the virtual apex of the hopper. Development of the consolidating stress within a bulk solid handled in a bin is shown in Fig. 19 .

The compressive stress  $\sigma_1$  causes consolidation (packing) of the bulk solid handled in the bin. The product get strength. Strength development of a bulk solid in a bin may be represented by the unconfined yield stress  $\sigma_c$  (Fig. 19). It shows a profile similar to that of the consolidating stress  $\sigma_1$ . Note the product strength at the top surface as well as at the discharge hopper's virtual apex will be zero for free-flowing bulk solids only but show a positive value for cohesive bulk solids

Imagine now that a cohesive arch has formed at some point of the converging hopper. In effect the bulk solid consolidation in the bin is sufficient that a stable structure can form which spans the bin outlet, supports the weight of above product column and transfers it to the wall of the hopper. Experience teaches that the *bearing stress*  $\sigma_a$  of a cohesive arch is proportional to its span  $D_a$ . I.e. that the bearing stress  $\sigma_a$  will linearly increase for the bin's discharge hopper section but remain constant for its cylindrical section. A graphical representation of the relation bearing stress  $\sigma_a$  versus arch span  $D_a$  is shown in Fig. 19 .

Figure 19 Analysis for flow



The lines representing the arch bearing stress  $\sigma_a$  and the unconfined yield stress  $\sigma_c$  are intersecting. The intersection defines a critical dimension for formation a cohesive arch:

- ◆ for positions above the intersection bulk solid strength is not sufficient to support a stable cohesive arch,
- ◆ for positions below the point of intersection stable cohesive arches will form as the bulk solid has sufficient strength to support a stable arch.

Above observation allow the formulation of a flow - no flow criterion:

A bulk solid will flow as long as its cohesive strength is not sufficient to support the load of above product column

or

$$\sigma_c < \sigma_a$$

For a bin discharge hopper both the bearing stress  $\sigma_a$  of a cohesive arch and the consolidating stress  $\sigma_1$  are linear functions of the span width  $D_a$ . Furthermore each of these stresses approaches zero at the hopper's virtual apex. Hence it follows that the ratio  $\sigma_a / \sigma_1$  is a constant for a given hopper geometry. This ratio is commonly called a hopper's *flow factor*  $ff$  characterizes a hopper's manner of discharging the contained bulk solid. Note that flow factors have been calculated by Jenike for a wide range of hopper types.

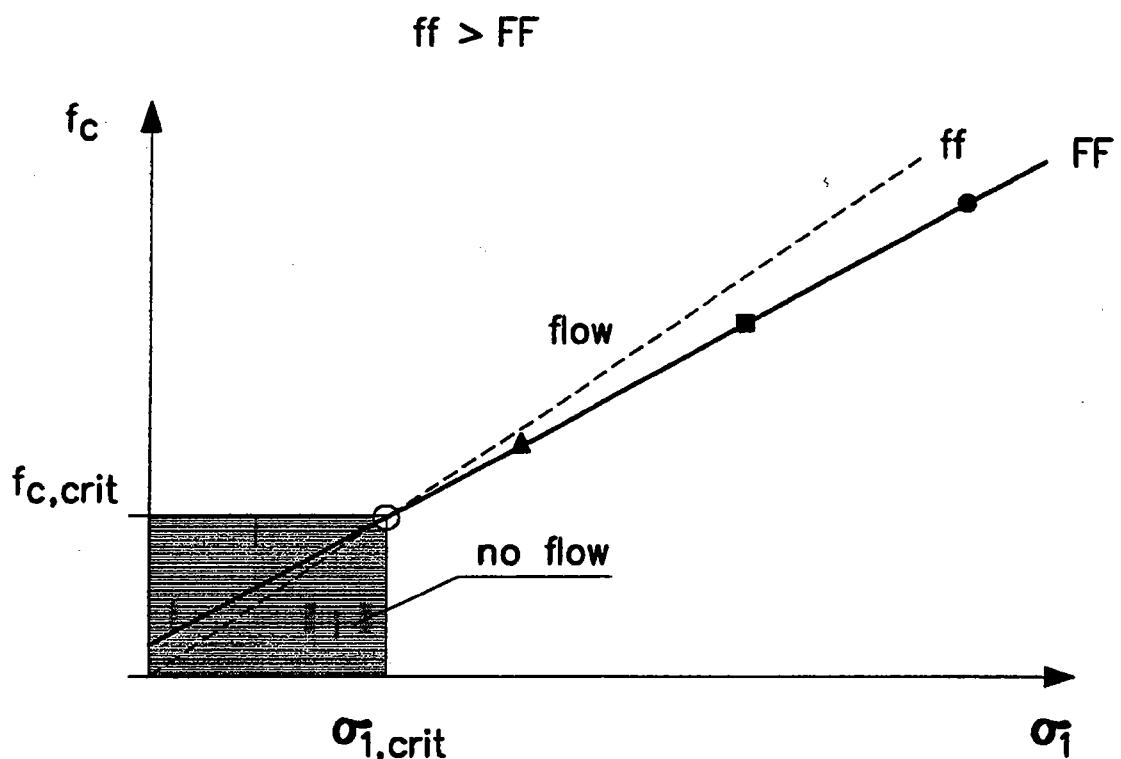
Flow factor  $ff$  and flow function  $FF$  ( $= \sigma_c / \sigma_1$ , i.e. the ratio of unconfined yield stress versus consolidating stress) will intersect when plotted in a common stress diagram (see Fig. 20+15). The intersection represents again critical flow condition what allows for a further formulation of the flow - no flow criterion:

A bulk solid will flow at all conditions for which the  $FF$  line lies below the  $ff$  line

or

$$FF < ff$$

Figure 20 The flow - non flow criterion



## 4.2 Design Criteria for new Bins

### 4.2.1 Design Concept

The design of bins and silos can be based on two concepts, either

- ◆ on the mass-flow concept, or
- ◆ on the funnel flow concept.

An evaluation of both concepts (see Fig. 21) shows clear operation advantages for the mass-flow concept but also its limited qualification for the storage of huge product volumes.

The funnel-flow concept is the preferred concept for large volume stores. It is considered an acceptable selection in cases

- where non-cohesive (free-flowing) products are involved,
- where product segregation is unimportant,
- where product degradation is not likely to be a problem,
- where feed rate consistency is not of prime importance.

The mass-flow concept is the preferred concept for feed bins. But this concept is also recommended for storage purpose

- with cohesive products,
- where qualitative consistency of the reclaimed product is important,

There are some general principles to be observed when designing bulk solid handling systems:

Rule 1: The demands on a large volume store are different from that on a feed bins where reliable product reclaim is prerequisite.

> As a consequence storage and process feed functions should be separated whenever possible.

Rule 2: Feed bins should be designed for reliability of reclaim. This is much easier for small than for large feed bins.

> As a consequence feed bins should be designed for the lowest possible volume but never be abused for additional storage capacity.

Rule 3: Optimum process operation and consistency of product quality is function of consistent and reliable rate control of the components.

> To meet this aim feed bins should be designed for mass-flow on principle.

Bin dimensions

Figure 21 Funnel flow versus Mass - flow

	Funnel-flow	Mass-flow
Bin shape	Compact flat hopper	Slender steep hopper
Flow sequence	First-in Last-out	First-in First out
Discharge order	Loading order inversed	As loaded
Silo utilisation	partial only	complete
Handling problems		
– discontinuous flow	arching, rat-holing	arching possible
– no flow	erratic flow, flushing	–
– lump formation hang-ups	possible	–
– product degradation	possible	–
– segregation		counteracted

Precondition for mass-flow to develop in a bin are

- ◆ a discharge hopper which is sufficiently steep as to initiate product flow along its walls,
- ◆ a hopper outlet which is sufficiently wide to prevent formations of any obstructions to flow,
- ◆ a hopper outlet that is fully active.

Comment:

- ◆ Dimensioning of new bins and silos should always be based on the tested flowability characteristics of the product in question independent of the selected bin design concept (mass-flow or funnel-flow). Worst product conditions should be considered when designing the shear test program (e.g. moisture levels valid for the wet season).
- ◆ For a given product the maximum permissible hopper half-angle  $\theta_c$  is smaller for a conical hopper than the half-angle  $\theta_p$  for a plane flow hopper. In addition the required minimum opening width  $D_c$  for a conical hopper is typically twice as wide as the minimum opening width  $D_p$  for a wedge type hopper. Hence it is clear that the plane-flow hopper concept makes better use of available headroom than conical hopper concept.
- ◆ For cohesive (sticky) products reclaim at low rates just by gravity may not be possible as full activation of the required wide outlets is not ensured. In such cases the application of appropriate discharge aids must be considered in the Bin/Feeder concept.

#### **4.2.2 Product Reclaim Systems**

Reliable operation of any rate control device depends on consistency of bulk solid supply out of the feed bin. Feeders are typically designed for two functions

- ◆ as a discharge aid which activates the bin outlet, and
- ◆ as a means of controlling the feed rate to the following process.

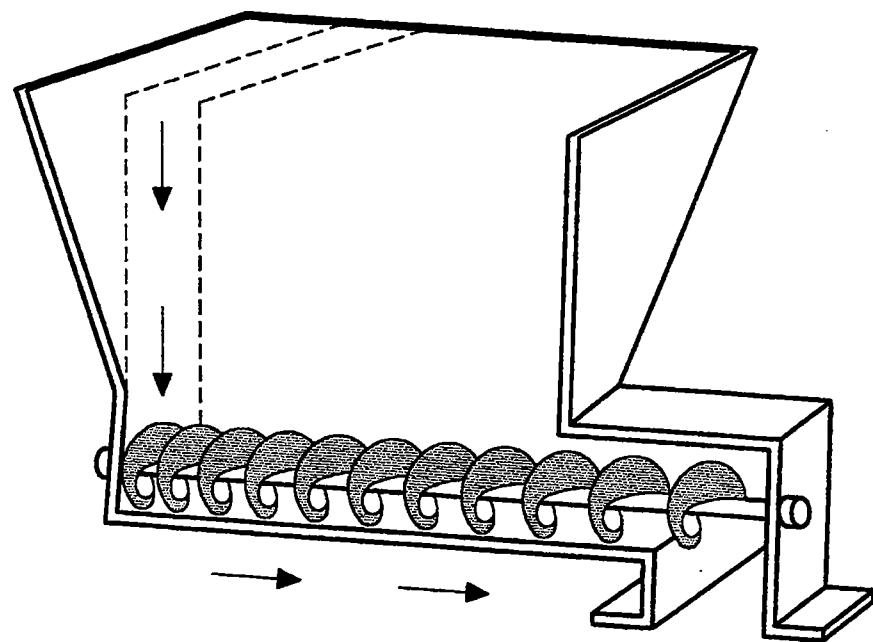
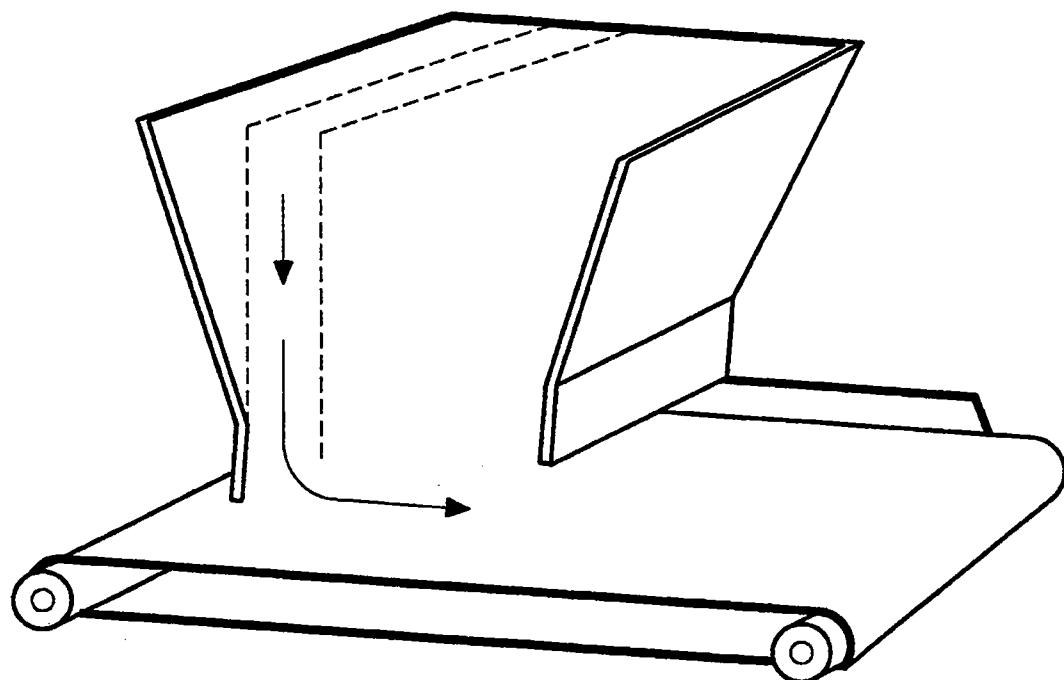
Experience teaches that arching and rat-holing may occur even with bins that have been designed for mass-flow according to the rule of (Jenike's) art. This kind of problems can typically be related to partial activation of the bin outlet, resulting in subcritical dimensions of the activated area and causing erratic or even interrupted flow. There are two reasons for partial bin outlet activation

- ◆ a closed design of the bin/feeder interface,
- ◆ a low discharge rates with cohesive bulk solids.

Bin/feeder interfaces are designed as closed as possible as to prevent spillage and facilitate housekeeping. With such designs product will be activated only in a narrow zone at the rear end of the feeder as that is the only area where free volume is created for the product to flow in (Fig. 22). Activating a bin outlet means that free volume must be created over the outlet's full length. This can be achieved by expansion of the bin/feeder interface as shown in Fig. 23, 1-3, or by means of live bottom feeders.

For cohesive (sticky) products reclaim at low rates just by gravity may not be possible as full activation of the required wide outlets is not ensured. In such cases the application of appropriate discharge aids must be considered as aeration systems for dry powders, vibrating cages for cohesive products, rotary extractors for sticky products

**Figure 22 The problem of the partial outlet activation**



**Figure 23.1 The concept for full outlet activation: the expanded outlet**

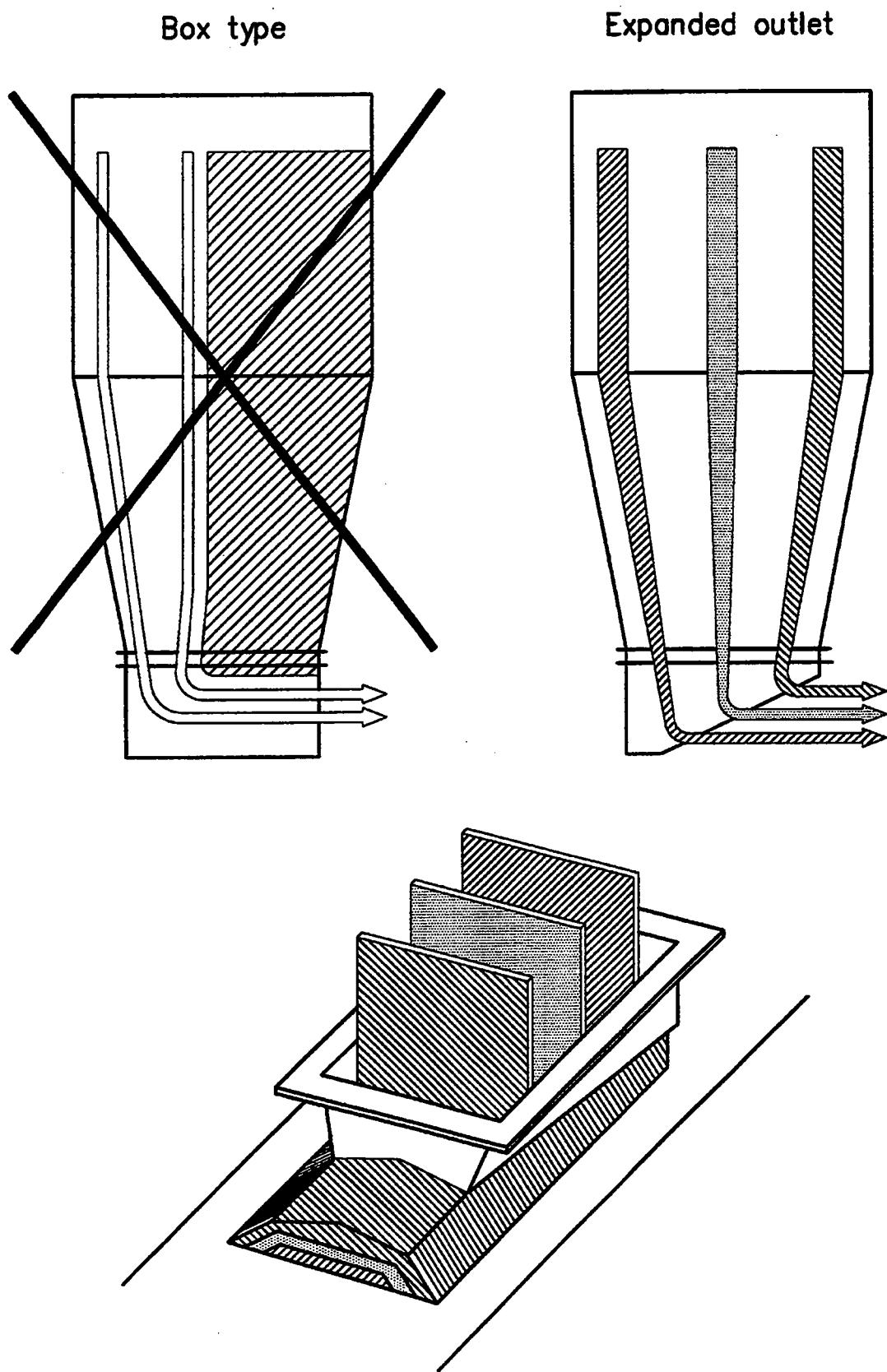


Figure 23.2 The concept for full outlet activation

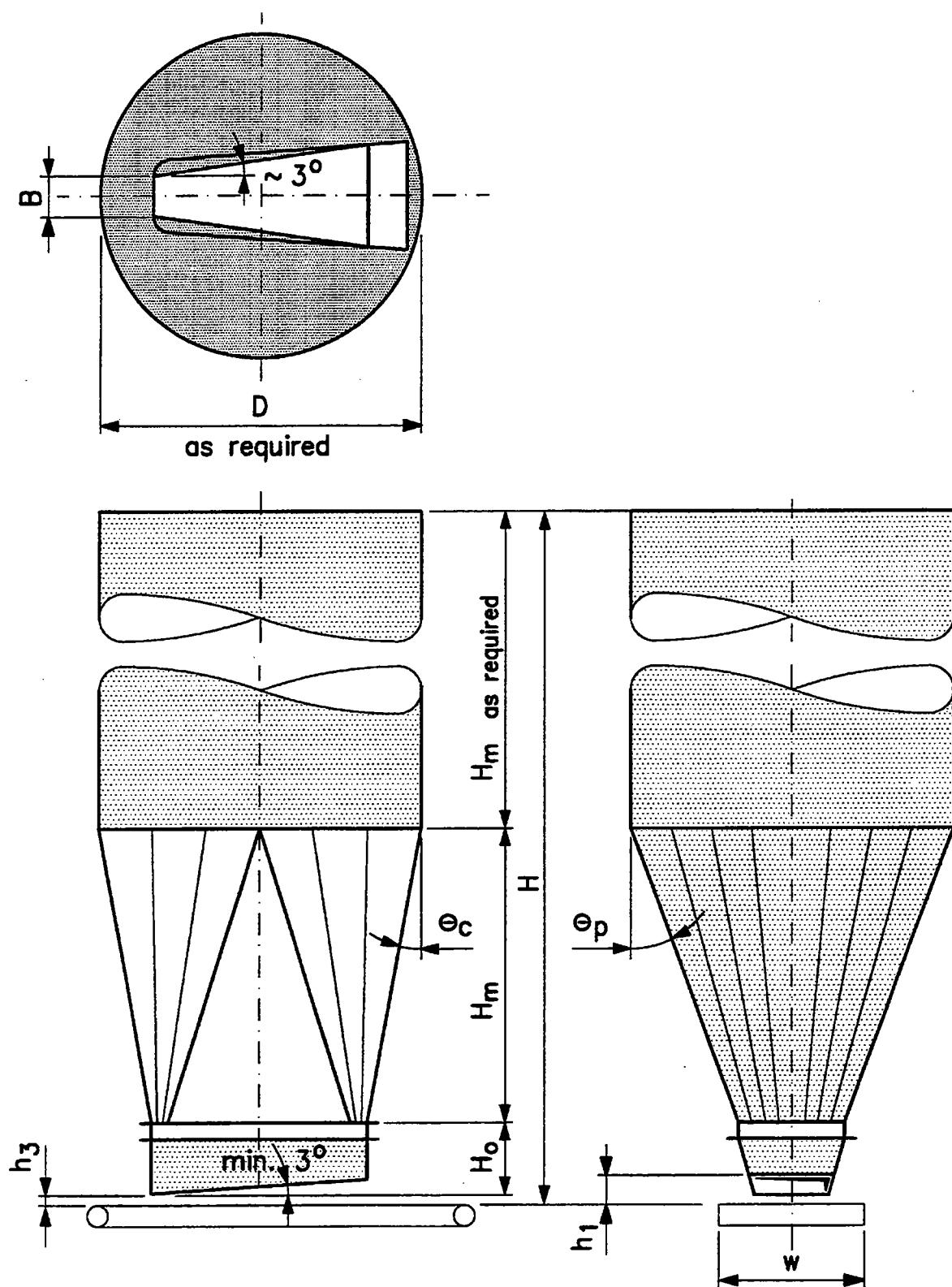


Figure 23.3 The concept for full outlet activation the tapered box

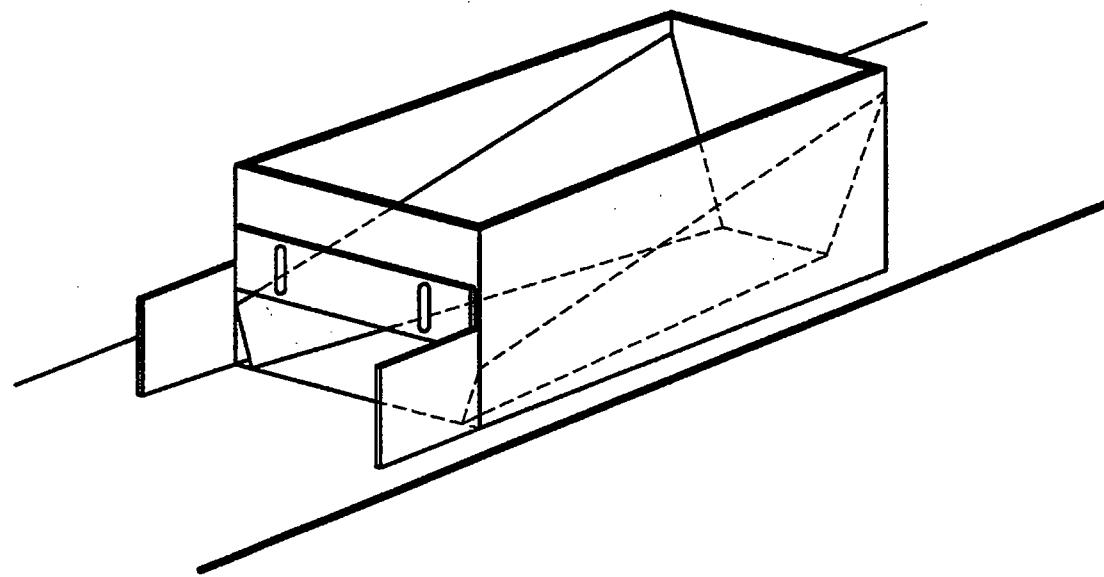
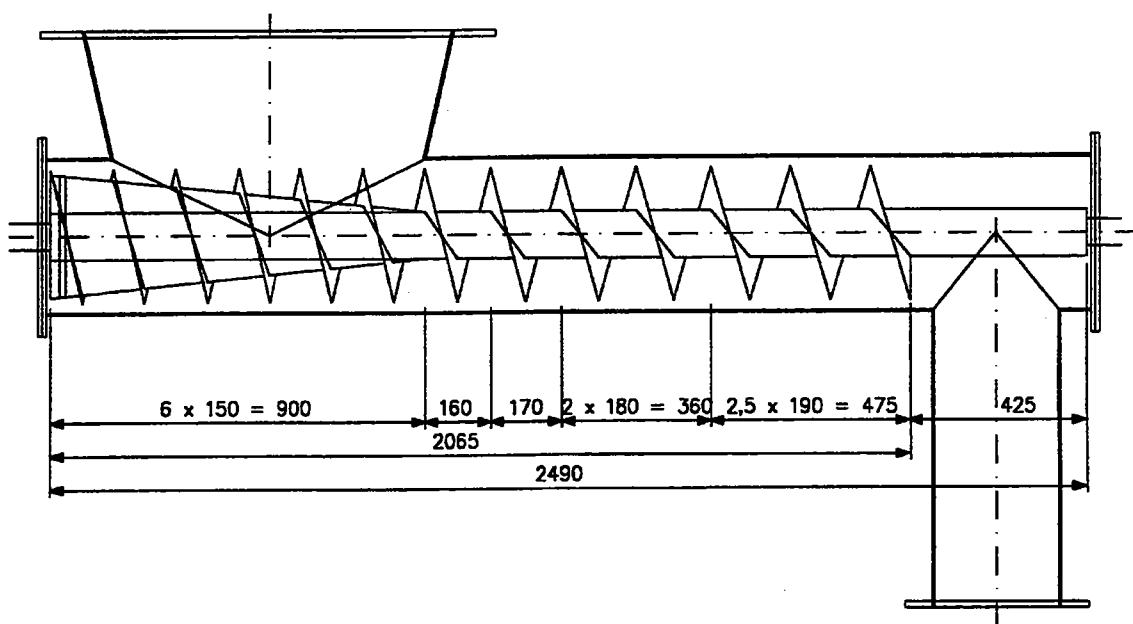


Figure 23.4 The concept for full outlet activation the screw feeder



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